A MODEL SOLUTION FOR TRACKING POLLUTION

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In the U.S., operators throughout the chemical process industries are being pressed by a strong environmental force — the 1990 Clean Air Act Amendments (CAAA). Far broader than the narrowly focused Clean Air Act of 1970, the latest amendments have been designed to sharply reduce smog, acid rain and various environmental pollutants in the earth's atmosphere.

Combined with individual regional and state regulations, the CAAA declare that all major sources of air pollutants (plants emitting 10 tons/yr of any listed pollutant, or 25 tons/yr overall) will be compared against 12% of their competitors' most tightly controlled plants and will be expected to perform at that benchmark level. New plants will be required to beat the best-controlled plants in the industry, from an emissions standpoint.

Emissions must be 'monitored'

To ensure compliance with these new and more-stringent standards, process facilities must know the quantity of air emissions continuously, especially sulfur dioxide (SO_2), nitrogen oxides (NOx), carbon monoxide (CO) and total reduced sulfur (TRS). In many cases, the opacity of effluents will also have to be carefully watched and controlled.

The traditional technology uses continuous emissions monitors (CEMs), which track the emissions from individual sources, such as industrial and utility boilers (Figure 1a). Such systems use extractive analyzers to monitor emissions continuously, and include supporting electronic and computer hardware, personnel, and logistical facilities.* The initial cost of a CEM (including the requisite sensors, supporting electronics and building space) can exceed $200,000, with ongoing maintenance costs to follow. Nonetheless, for many firms, this is seen as a cost of doing business in today's highly regulated environment. When redundant CEMs are needed, monitoring expenses can add even more significantly to the cost of the overall operation.

* See Pick the right emissions monitor, *Environmental Engineering*, a supplement to *CE*, June 1993, pp. 4-9.

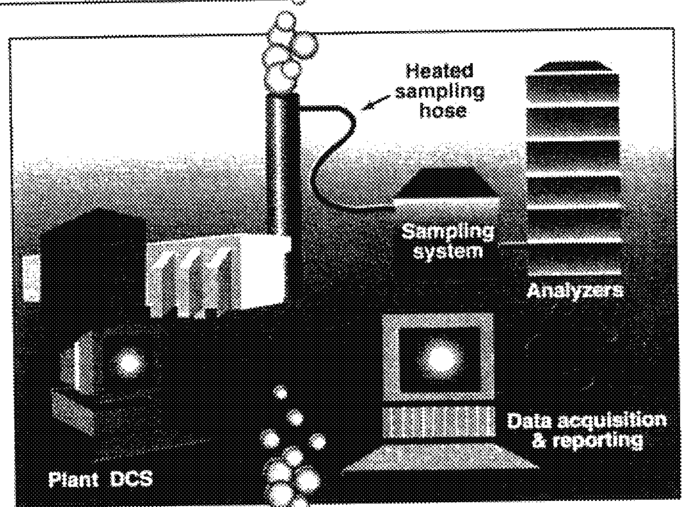

FIGURE 1A (top). A traditional hardware-based continuous emissions monitor is both capital and maintenance intensive, since it often requires heated sample lines and extensive corrosion proofing

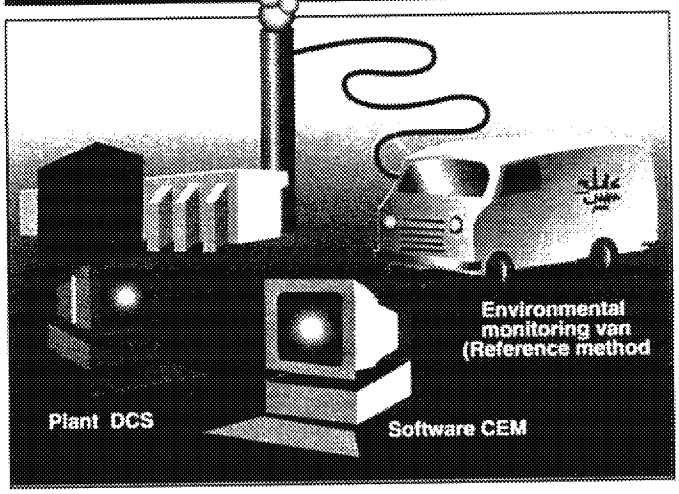

FIGURE 1B (bottom). Meanwhile, the use of a predictive software model reduces both capital and operating costs. A mobile CEM is brought onsite to gather actual emissions data during startup, and is used periodically to re-calibrate the model

ROBIN PELKKI

Replace hardware emissions monitors with adaptive modeling software — and save

Process modeling: Not enough

For years, engineers have sought to create mathematical models of their processes to better control them. In principle, any process can be faithfully modeled so that the model can "predict" downstream process output based on

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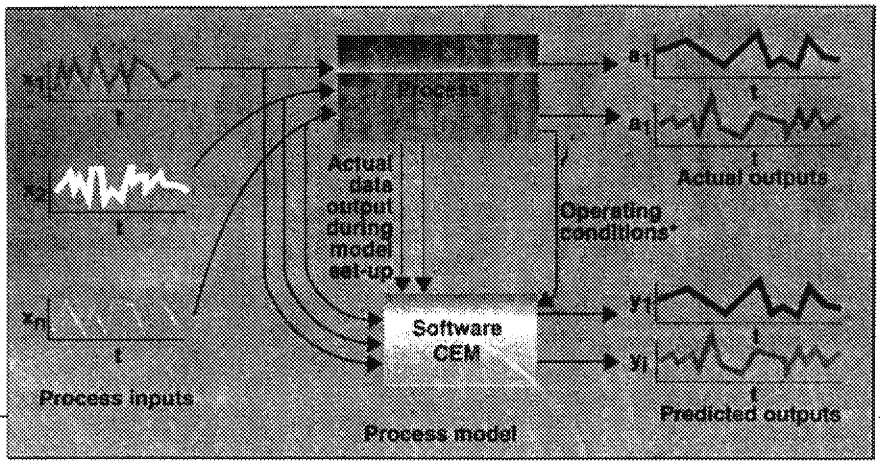
FIGURE 2. During software setup, input and output data are provided to the software to model the process. For a gas-fired boiler, process inputs include the temperature and pressure of the fuel, inlet air and fluegas, the fuel flowrate, and the damper postion



*During operation, key operating parameters, such as temperatures and pressures, are continuously provided to the model, which provides predicted outputs in real time

FROM CONCEPT TO IMPLEMENTATION IN 60 DAYS

In May 1991, Arkansas regulators granted Arkansas Eastman permission to construct and operate a new 221-million-Btu boiler, with a maximum of 21.96 lb/h of NOx emissions. The boiler received online regulatory certification in August 1992, and existing regulations required that NOx output be continually monitored or mathematically estimated within 360 days.

The plant wanted to avoid the heavy initial cost ($200,000+), ongoing maintenance, dedicated personnel and support systems required by a traditional hardware-based emissions monitor. In early 1993, the company asked the Arkansas Dept. of Pollution Control and Ecology (ADPCE) to consider the use of adaptive modeling technology as an alternative. The regulators agreed to an online trial and verification of relative accuracy.

In March 1993, Pavilion Technologies' Process Insights and Software CEM adaptive modeling software was developed and installed on an existing Digital VAX computer at the Arkansas Eastman site. During the model's training period, NOx emissions data were collected using portable monitoring equipment and regulatory-approved monitoring methodology.

The plant's distributed control system (DCS) monitored 21 key process variables simultaneously.The final data collection and training process took about a week. Within three weeks, the model was trained for all operating conditions within the full range of the boiler, and provided satisfactory correlation between actual and predicted results (Figure 3).

Shedding light on the process

In addition to its value as an emissions monitor, the package had added value in that it can recommend operating practices that would better control boiler operation and reduce emissions. By showing that the temperature of the boiler economizer had a far greater effect on emissions than was previously anticipated, the model provided great insight into the relationships between process variables and emissions.

On May 12, 1993, representatives from ADPCE witnessed a demonstration of the adaptive model predicting boiler emissions. They judged the method to be at least as accurate as a standard hardware CEM.

For any emissions monitor, state requirements call for an annual relative-accuracy test, to be conducted by an independent third party. On June 9, 1993, such a test was performed by Ramcon Environmental Corp. (Memphis, Tenn.), and showed that the Software CEM met the ±20% relative-accuracy requirements dictated by EPA's CEM regulations. Arkansas Eastman operators are expecting single-digit accuracy, as more experience is gained in training the model. Since regulations also require periodic calibration checks, Arkansas Eastman will bring in portable emission-testing equipment twice a year. During each one-week calibration check, the model will also be retrained.

An added benefit of the system is that should a sensor fail during boiler operation, the Software CEM system will trigger a DCS alarm, and will provide calculated estimates until the sensor is back online. At the Arkansas Eastman facility, the sensor-validation program has demonstrated that up to five process sensors can be in error without compromising the model's mandated prediction accuracy. After regulatory approval was granted to develop the Software CEM, the project took less than 60 days to move from conceptualization to implementation. To date, online time has exceeded 99%. □

upstream process behavior. In practice, however, many operators have found the existing tools to be inadequate to model complex, real-world processes.

Most models are steady-state, linear approximations based on a select number of process variables. The result is a coarse approximation of the process. Larger, more-accurate models can be developed through controlled experiments, but these are expensive, may require plant downtime, and usually call for specially trained employees to design and analyze them.

Another methodology relies on a group of techniques broadly called model-based predictive control. These multivariable, database-modeling methods also assume that process dynamics can be simulated through linear approximations of a few key variables. However, since most processes involving combustion and heat transfer are inherently non-linear and highly dimensional, such mathematical models have also been found to lack the accuracy required to predict air emissions in accordance with regulatory requirements.

Enter adaptive modeling

Adaptive modeling software integrates three contemporary technologies — neural networks, fuzzy logic and chaotic systems theory — into a software package that can be readily used by the average engineer (box, p. 35). This produces a powerful and accurate paradigm for the 1990s: The ability to model dynamic, non-linear processes.

Adaptive technology is well-suited for modeling the processes that typically generate air emissions. Not only do these programs enable process engineers to faithfully and flexibly predict process behavior, but they provide direct insight into the process variables that have the largest impact on the production of the toxic air emissions.

Commercially available programs can provide setpoint recommendations, which often allow the user to reduce op-

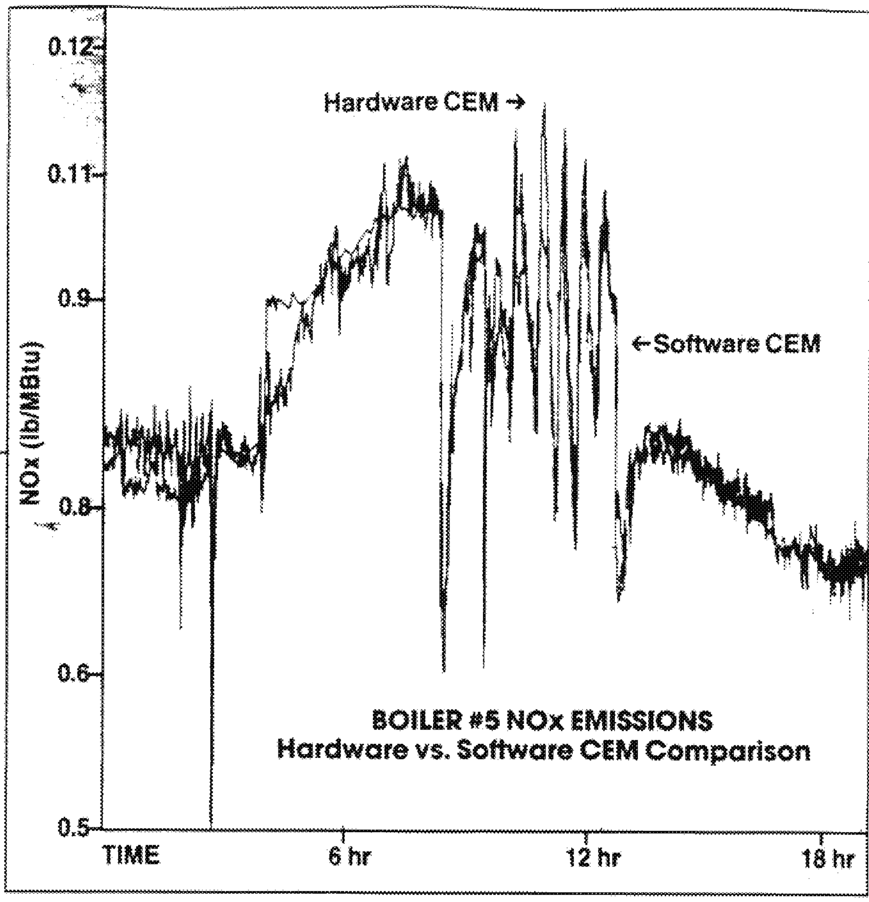


FIGURE 3. This plot shows a close fit between actual and predicted NOx emissions from one of Arkansas Eastman's gas-fired boilers

THE SOFTWARE TOOLBOX

Neural networks are a powerful set of mathematical techniques that "learn" complex, non-linear processes directly from historical data. Once trained, the neural networks can faithfully model the process and predict process outputs based on varying process behavior. When coupled with analytical and predictive techniques used in the study of chaotic systems, neural networks have proven their value in converting historical operating data into process models.

Fuzzy logic is a branch of mathematics based on the idea that traditional true-or-false logic cannot deal with situations that contain exceptions. "Fuzzy rules" replace deterministic mathematical precision with the intuitive logic that an expert operator uses.

Fuzzy logic is particularly suited for complex processes such as those with multiple inputs and outputs, which would be difficult or impossible to simulate with traditional mathematical models. Such logic has been extensively applied in process control, typically for applying "fuzzy" or "soft" constraints to operating variables. For example, a control program can be told: "Keep the pressure generally below 100 psi, and never let it exceed this value." Fuzzy rules are softer and more intuitive in their application, and are a natural complement to neural networks.

Chaos theory addresses how irregularities — in process behavior, for example — evolve over time. Since many chemical processes defy prediction through traditional mathematical modeling, chaos theory helps engineers model and predict process operations in the face of mathematically or statistically unpredictable process behavior.

Adaptive software combines all three of these mathematical tools into a single process model. Simplistically, the neural net models the process, fuzzy logic applies intuitive operating constraints, and chaotic systems theory keeps the modeling process on track in the face of unpredictable process behavior. ❐

erating costs while simultaneously increasing efficiency and lowering emissions. In this manner, the model should not be viewed as a regulatory burden, but as a pollution-prevention tool and potential source of improved profitability for the company.

Experience at the plant site

One such model, The Software CEM, is marketed by Pavilion Technologies (Austin, Tex.), and is based on an application developed at the Arkansas Eastman Div. of Eastman Chemical Co. (Batesville, Ark.). The software model has been running under a state-issued operating permit at Eastman's Batesville site since July 1993 (box, p. 33). The Software CEM models processes that produce air emissions, such as industrial boilers, and predicts emissions based solely on behavior of the process (Figure 2).

In what may be the beginning of an interesting regulatory trend, Arkansas and Texas have now approved the use of adaptive software to predict emissions, in lieu of traditional emissions-monitoring systems. This substitution is decided on a case-by-case basis during permitting.* It should be noted that certain monitoring requirements under CAAA's New Source Performance Standards (NSPS) and National Emissions Standards for Hazardous Air Pollutants (Neshaps) may limit, or exclude, the use of this technology.

During the preparation stage, the Software CEM must first be "trained," using historic operating and emissions data. The model is only as accurate as the input data. Such emissions data are gathered over the typical range of operating rates, using a conventional CEM system installed in a portable monitoring trailer. The collection of real-time process and emissions data is facilitated by the use of a supervisory data-collection and storage system.

Once trained to model the operation, the system will use real-time operating data from plant instruments and the distributed control system to predict emissions rates that would otherwise be measured with a hardware CEM system. Since the methodology is generic, it can be customized to provide accurate measurements of NOx, SO_2, CO and other regulated pollutants.

In addition, the software creates a "sensor validation model," which detects the failure of critical process sensors and maintains the accuracy of the emissions prediction. This is essential, since about 15 to 30 sensors are typically required to provide continuous,

* For a related story in this issue, see Gearing up for Title V operating permits, p. 14-24.

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real-time input to the model during process operation. For a gas-fired boiler, input data such as the temperature and pressure of the inlet air, natural gas and fluegas, the fuel flowrate and damper position are required.

Once a sensor malfunction has been detected, the model generates an alarm for the process operators. The model then replaces failed sensor data automatically, using reconstructed values until the sensor is back online. These values, calculated from recent historic data, are sufficiently accurate to maintain mandated emissions-prediction accuracy. All emissions values predicted by the program are automatically sent to the process operator's control computer and the plant database system.

Born to sing backup

Many companies already have hardware CEMs in place to meet evolving CAAA monitoring requirements. Some are also considering redundant CEM systems to meet regulatory standards that require that substitute data be estimated and reported in the event of CEM downtime (40 CFR Part 75). In addition to their role as the primary CEM, adaptive software programs also function well as a low-cost redundant system. Where allowed, this new technology is capable of meeting or exceeding CEM performance and has the added value of being a tool for waste minimization and pollution prevention through process optimization. ■

Edited by Suzanne Shelley

Suggested reading

1. Fuzzy logic: More than a play on words, *Chem. Eng.*, February 1993, pp. 30-33.
2. Neural nets: They learn from examples, *Chem. Eng.*, August 1990, pp. 37-45.
3. The simple rules of complexity, *Chem. Eng.*, July 1991, pp. 30-35.
4. W.T. Miller, R. S. Sutton and P.J. Werbos, "Neural Networks for Control," MIT Press, Cambridge, MA, 1990.
5. B. Kosko, "Neural Networks and Fuzzy Systems: A Dynamical Systems Approach to Machine Intelligence," Prentice Hall, Englewood Cliffs, N.J., 1991.
6. Les Kane, How combined technologies aid model-based control, *Hydrocarbon Processing*, May 1993.

Additional resources

1. Software — John Havener, Pavilion Technologies, Inc., 12112 Technology Blvd., Austin, TX 78727-6298; Tel: 512-250-3150.
2. Consulting and Technical — Dr. Richard Martin, Callidus Technologies Inc., 7130 South Lewis, Suite 635, Tulsa, OK 74136; Tel: 918-496-7587.
3. Stack Testing — William J. Sewell II, RAMCON Environmental Corp., 6707 Fletcher Creek Cove, Ramcon Bldg., Memphis, TN 38134; Tel: 901-387-0500.

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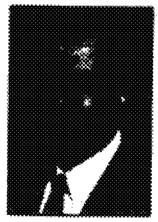

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